# IN3015 Quiz Notes

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## 1. Wave physics & apertures

**Q: What type of wave is used in ultrasound imaging?**
**A**: Mechanical longitudinal waves (sound waves). These are waves where the particle displacement occurs along the wave direction. Shear waves, where the displacement occurs perpendicular to the wave direction, can be used for elastography.

**Q: What are typical ultrasound frequencies?**
**A**: All frequencies above 2kHz are considered ultrasound. However, for medical ultrasound imaging the frequencies used are typically several MHz, depending on the specific application. For echocardiography, 2-4MHz is common.

**Q: Why do we use high-frequency waves for medical imaging?**
**A**: The short wave lengths in high frequency waves improves resolution, and allows for detailed images where we can observe smaller structures in the body. They also diverge less, giving a more focused beam.

**Q: What are the downsides of using high frequencies?**
**A**: The main downside with using high frequencies is that the level of penetration decreases. This is because high frequency waves experience greater attenuation in the tissue. There is always a trade-off between depth/penetration and resolution, which is why we use different frequencies for different applications. If we are imaging structures close to the skin, it's reasonable to use high frequencies to maximize resolution, as we don't require high penetration depth.

**Q: What are the reflection and transmission coefficients?**
**A**: These coefficients tell us the amount of wave reflection and transmission ocurs when a wave propagates through a boundary. When this happens, part of the wave is transmitted through the boundary, and another part is reflected. These coefficients give us the pressure ratio between the incoming wave and the transmitted/reflected parts:

$$R = \frac{p_r}{p_i} \quad T = \frac{p_t}{p_i}$$

**Q: What is acoustic impedance and how does it relate to ultrasound imaging?**
**A**: Acoustic impedance characterize how the sound waves permeate through a given material, and is defined as $Z = \rho_0 c_0$. Transmissions and reflections only happen when waves propagate through a region with a change in acoustic impedance, and these reflections make up the signal used in beamforming. In other words, ultrasound imaging cannot occur if there is no variation in acoustic impedance, as no reflections would occur.

**Q: What are the three types of scattering we consider in ultrasound imaging and when do they occur?**
**A**:

- Diffusive/Rayleigh scattering: occurs when the scatterer is much smaller than the wave length ($\lambda \gg a$) and results in a spherical scattering pattern. Includes living cells, blood cells.
- Diffractive scattering: occurs when $\lambda \approx a$. This includes small cysts or microcalcifications.
- Specular reflections: occurs when $\lambda \ll a$. This causes "simple" reflections and can be analyzed using the reflection/transmission coefficients and Snell's law.

**Q**: **What is meant by "acoustic reciprocity"**
**A**: Acoustic reciprocity means that the measured response does not change if we interchange the positions of the emitter (speaker) and the receiver (microphone). This is useful in ultrasound, as it lets us view small scatterers as point sources.

**Q**: **How do probes typically produce and detect ultrasound waves?**
**A**: Probes use small transducer elements which mechanically vibrate to excite pressure waves in the media. In practice, this is achieved by applying a voltage to the transducer elements, which then vibrate due to the direct piezoelectric effect. The same concept is used to detect incoming ultrasound waves, where voltage is generated through the inverse piezoelectric effect.

**Q**: **What is near field vs. far field?**
**A**: The near and far fields are characteristic regions of the pressure field emitted by the ultrasound probe. In the **near field**, the pressure field is chaotic, as the plane wave interferes with the edge waves produced by the transducer piston. In this area, we observe many maxima and minima in the pressure field. In the **far field**, we observe a smooth decay in the pressure amplitude in the axial and radial directions, as the simple plane waves dominate and dont interact much with the edge effects, and the wavefronts from individual piston positions are almost in phase.

**Q**: **Do we typically operate in the near-field or far-field in medical ultrasound imaging?**
**A**: The near-field.

**Q**: **How can we reduce side lobes in the pressure field?**
**A**: Side lobes can be attenuated by apodization, decreasing aperture size and by using pulsed excitations (many frequencies).

**Q**: **What are the two main ways of producing focused transmits?**
**A**: Mechanically, using curved elements or physical lenses. Electronically, by appropriately delaying transmits from different elements.

**Q**: **In the context of transducer arrays, what is menat by pitch, element and kerf width?**
**A**: The pitch of an array is the distance between the center of adjacent elements. The kerf width is the width of empty space between element edges. The element width is the width of the elements themselves (the pistons).

**Q**: **What is meant by the lateral and axial resolutions?**
**A**: The lateral resolution is the ability to distingiush between objects with equal depth but different lateral positions. Similarly, axial resolution is the ability to distinguish at varying depth.

**Q**: **What is "depth of field"**
**A**: The depth of field of a focused transmit is the "length" of the area of focus (the focal zone). This is measured by thresholding the pressure magnitude in the focal zone.

**Q**: **What is a point spread function**

**A**: The point spread function tells us how an ultrasound imaging system captures a point in an image. This is a nice, simple way to characterize an imaging system, and lets us easily compare the resolutions obtained with different imaging methods.

**Q**: **How does the DAS algorithm work?**
**A**: In the Delay-And-Sum algorithm, we perform "receive focusing" by assuming that the imaging area consists of many small, diffusive scatterers. A diffusive scatter source at a given position will cause an echo that reaches the probe elements at different times. The goal of the beamforming is to estimate the arrival time of this echo, such that the signals from all transducer elements can be combined to calculate the total intensity of the scatterer echo. For each element, a delay is calculated based on the position and transmit used, and these delays are used to "align" the signals. Then, these signals are added (potentially with apodization) together. The result is then used to color the pixel at the given position in the image.

**Q**: **What is speckle?**
**A**: When there are few scatterers in the scene, the signal received is simple, and individual scatterers are easily distinguished. However, when the scatter density is high (as modelled in the body), the echoes interfere with each other, causing a "random" (actually deterministic) signal at the transducer.

**Q**: **What is "plane wave decomposition"**
**A**: Plane wave decompositions describe arbitrary pressure fields as a sum of individual plane waves.

## 2. Ultrasound Processing

**Q**: **In short, what are the three main stages of the US chain considered in this course?**
**A**:

1. Transmit beamforming: Constructing the actual transmitted ultrasound signals (beam focusing, plane wave imaging, delays and apodization)
2. Receive beamforming: calculating and applying delays to the received data, combining the data across elements and multiple transmits.
3. Post processing: image filtering and other techniques for noise reduction.

**Q**: **What three types of waveforms are used in transmits?**
**A**: Planar, diverging and converging waveforms.

**Q**: **What are the four most used imaging modalities?**
**A**:

1. Plane wave imaging (coherent compounding)
2. diverging wave imagine
3. Synthetic transmit aperture imaging
4. focused imaging

**Q**: **Why is the concept of the "general beamformer" important**
**A**: The general beamformer formulation allows us to use the same techniques for different imaging modalities, as long as these modalities are modelled according to the general beamformer formulation. This amounts to defining the wave as coming from single point source (whether or not this is physically accurate).

**Q**: **Where is the (general beamformer) point source of a plane wave or diverging wave?**
**A**: For a plane wave, the point source is modelled as infinitely far away, while for a divering wave, the point source lies somewhere behind the transducer array.

**Q**: **How does coherent compound plane wave imaging work? How does this compare to coherent diverging wave imaging and FI?**
**A**: In CPWI, several plane waves are transmitted in succession, with different directions. The received signals from these plane waves are combined with some apodization scheme to form a single, fully lit ultrasound image. Coherent DWI and FI works similarly: several transmits of the same type are steered in different directions, and these are combined into a single frame. The difference is the type of waveform used.

**Q**: **What is STAI**
**A**: In STAI, only one element fires per transmit, while all elements receive for all transmits. This results in many low-res images which are combined to obtain a high-res image. Since only one element transmits at a time, the frame rate is highly limited.

**Q**: **What are the three ways of storing the received data?**
**A**:

- RF (radio frequency): the raw data, directly as sampled.
- Analytical signal: The data represented with complex numbers, after applying the hilbert transform
- IQ: IQ-modulated data, where knowledge about the signal bandwidth is exploited to represent the signal compactly (In-phase quadrature).

**Q**: **How should one choose an appropriate sampling frequency?**
**A**: The nyquist sampling criteria gives us a lower bound for the sampling frequency to perfectly reconstruct the signal: **twice as fast as the highest frequency component**. Typically, we oversample, to make filtering easier.

**Q**: **How do we find the envelope and what is this used for?**
**A**: The envelope is found by taking the absolute value of the analytical signal. This is the signal that is used to display the data in the ultrasound image, as the envelope is a more intuitive representation of the strenght of the signal.

**Q**: **Why is IQ-data useful?**
**A**: IQ-modulation effectively compresses the signal, which reduces memory consumption. It also represents the signal as complex data, which is necessary for some US techniques.

**Q**: **Explain the quantities in the generalized beamformer equation**
**A**: The beamformer equation:

$$b_{DAS}(x,z) = \sum_{a=1}^{N_a} \sum_{m=1}^{N_m} w_a^{tx}(x,z) w_m^{rx}(x,z) s_{m,a}(x,z) e^{i2f_{demod}\Delta t/f_s}$$

For a given pixel location $(x, z)$:
$w_a^{tx}$: the transmit apodization
$w_m^{rx}$: the receive apodization
$s_{m,a}$: the delayed signal strength
$e^{i2f_{demod}\Delta t/f_s}$: up-mixing in the case of IQ **Q**: **write down the simplified equation and explain the assumptions made**
**A**: We can simplify by dropping the pixel notation $(x, z)$. We can also assume that he transmit

apodization used is the same for all elements of the same transmit, letting us pull $w_a^{tx}$ out of the inner sum. Finally, if we assume the signal is analytic, we can drop the up-mixing factor as $f_{demod} = 0$:

$$b_{DAS} = \sum_{a=1}^{N_a} w_a^{tx} \sum_{m=1}^{N_m} w_m^{rx} s_{m,a}$$

**Q**: **What is beamspace and pixel space?**
**A**: In beam-space, the coordinates are the azimuth axis and depth axis. This is a convenient way of representing beam data, but is unintuitive when visualized directly. In pixel space, the axes are cartesian, and this is the way the results are visualized on an ultrasound machine. To do this,we must calculate transform from beam-space to pixel-space by appropriately sampling the beam-space data, for each pixel location. This is referred to as "scan conversion".

**Q**: **What quantities must be calculated to estimate the delays used in DAS?**
**A**: We need to calculate the transmit and receive distances (and an assumed speed of sound) to calculate the total time delay to use for the given element. The receive part is independent of imaging modality (we assume diffusive scattering) while the transmit part depends on the type of wave used.

**Q**: **How is the receive distance calculated?**
**A**: The receive distance is simply calculated as the euclidean distance from the scatterer/pixel to the given element:

$$R(x, z) = \sqrt{(x - x_{element})^2 + (z - z_{element})^2}$$

Usually, $z_{element} = 0$

**Q**: **How is the receive delay calculated for a diverging transmit?**
**A**: Using a virtual point source $(x_s, y_s)$behind the transducer, we can calculate the distance by:

$$T_{DW}(x, z, x_s, z_s) = \sqrt{(x - x_z)^2 + (z - z_s)^2}$$

**Q**: **What is apodization?**
**A**: Apodization is a weighting of different transmits or elements. This allows us to focus on areas where we expect high quality echoes, and can help in reducing noise and side lobes.

**Q**: **Explain receive apodization**
**A**: The receive apodization scheme determines how to weight the signals from different receive elements, as they are summed together when calculating the intensity of a position for a single transmit.

**Q**: **How is transmit apodization used for scan-line imaging?**
**A**: In scan-line imaging, the transmit apodization is used to mask out only one line for each transmit, along the focus beam. These lines are combined to construct the final image. This means we need to perform N transmits for an image with N columns.

**Q**: **How is the calculated signal strength transformed to the pixel intensity level observed on the ultrasound machine?**
**A**: First, the hilbert transform is used to obtain the analytical signal, which we then perform envelope detection on. Then, we apply log-compression. Without applying the logarithm, most regions will be very dark, as there is usually a wide range of intensities in the image, most of which are very weak. Finally, we can specify a signal floor/ceiling which thresholds which values get filtered out (rejected) or saturated (capped to max pixel intensity).

## 3. Image Post Processing and Quantification

**Q: What is coherent and incoherent compounding?**
**A**: Coherent compounding is used to combine data from multiple transmits to form a single image:

$$b_{DAS} = \sum_{a}^{Na} w_a^{tx} b_a^{\overline{Rx_{DAS}}}$$

Where $b_a^{\overline{Rx_{DAS}}}$ is the result of the receive beamforming.

As the equation suggests, in coherent compounding, we simply sum the RX beamformed signal, weighted by the transmit apodization. For coherent compounding, we instead sum the absolute values (the envelope):

$$b_{DAS} = \sum_{a}^{Na} \left| w_a^{tx} b_a^{\overline{Rx_{DAS}}} \right|$$

**Q: Why are moving targets problematic in compounding?**
**A**: When we do coherent and incoherent compounding, we are combining transmits taken in succession, at varying times. If the target moves significantly during the time it takes to complete all transmits, the signals can no longer be combined straight-forwardly, and doing so results in a degraded image. This is analogous to the blur that happens in photography when the shutter speed is too slow or the target is moving too fast.

**Q: What is MLA?**
**A**: Multiple Line Acquisition is a transmit apodization scheme used to compound focused image transmits. It is similar to scan-line imaging, except multiple adjacent lines are used per transmit. A binary line mask can be used, or one that decays away from the focus axis.

**Q: What is RTB? Explain the problem with overlap in RTB?**
**A**: Retrospective transmit beamforming is a transmit apodization scheme where we mask/weight the image according to the shape of the focused transmit. For focused imaging, this results in window which narrows to a point at the focal point, and then widens past the focal point. When these individual, masked transmits are compounded, we get high levels of overlap in the near and far regions, but very little overlap near the focal point. This can be adjusted for by amplifying regions with low overlap.

**Q: What is "well developed speckle" and how is it statistically modelled?**
**A**: Speckle occurs when the scatterer density is high, and is considered "well developed" when the density is greater than 10 scatterers per resolution cell. In this case, the pressure field is modelled as a circularly symmetric normal distribution.

**Q: How are speckle patterns reproduced in medical phantoms?**
**A**: For medical phantoms one can add a mix of small particles, like graphite powder.

**Q: What are the two main indicators used for evaluating the quality of an ultrasound image? Give an explanation for what these indicate**
**A**: <u>Resolution:</u> the ability to distinguish between adjacent scatterers of a certain size. "Given two scatterers with characteristic size $a$, how far apart must they be to be distinguishable from each other in the image?" This lets us pick out smaller structures in the body.
<u>Contrast:</u> the ability to distinguish tissue with different reflection coefficients (like organ boundaries)

**Q: What is "Full Width Half Maximum" and how is it useful in quantification?**
**A**: FWHM is the width of the main lobe at -6dB. This is useful in image quality quantification because the FWHM of point-spread function is a good way of measuring resolution.

**Q: How is the point-scatterer FWHM measured, in practice?**
**A**: We first image the point-scatterer with our ultrasound system. In a phantom, the point scatterer can be emulated by using a fishing line or something similar, where we image its cross-section. The FWHM can then be measured by plotting the amplitude of the data along a lateral line through the point in the image.

**Q: How is the axial resolution found?**
**A**: The axial resolution only depends on the transmit pulse, and is given by

$$z_{res} = \frac{cT_p}{2}$$

Where $c$ is the speed of sound and $T_p$ is the transmit pulse.

**Q: What's another way of measuring resolution**
**A**: The resolution can also be directly measured by observing the separability of two point scatterers. By defining a separability amplitude limit, one can measure the distance between the scatterers as this limit is reached.

**Q: What metrics are used to quantify the level of contrast in an image? What do we measure the contrast between?**
**A**: The two main contrast metrics are CR (Contrast Ratio) and CNR (Contrast-to-Noise-Ratio). We measure the contrast between some region of interest (like a cyst) and some background region. This gives us a good indication of how well we can pick out the structures we are actually looking for in ultrasound.

**Q: How is CR defined?**
**A**: CR is defined as the ratio between the mean of the region of interest and the mean of the background. Here, the mean is the expected value of the *power* of the linear scale, beamformed signal:

$$CR = \frac{\mu_{ROI}}{\mu_{BG}}, \quad \mu = E\left\{\left|b^2\right|\right\}$$

This metric is often given in logarithmic scale.

**Q: How is CNR defined?**
**A**: in CNR, we also consider the *variance* of the signals:

$$CNR = \frac{|\mu_{ROI} - \mu_{BG}|}{\sqrt{\sigma_{ROI}^2 + \sigma_{BG}}}, \quad \sigma = E\left\{(|b| - \mu)^2\right\}$$

## 4. Sonar

**Q: What is the two-way loss in sonar?**
**A**: The acoustic wave from a sonar transmit propagates spherically. This causes a geometric spreading loss of $1/R^2$. As the wave hits a scatterer, geometric spreading reoccurs, and the total two-way loss is $1/R^2$

**Q: Which aspects of the ocean environment affect sound propagation?**
**A**:

- seafloor
- sea surface
- salinity
- temperature

- water movement (currents, turbulence)

**Q**: **What is Medvin's formula**
**A**: Medvin's formula is an empirical formula for estimating the sound velocity at a given depth, salinity and temperature. This formula was obtained empirically through velocity measurements.

**Q**: **What do we mean when we say that sound is "lazy"**
**A**: By lazy, we refer to the tendency for sound to refract towards media where the sound velocity is lower (the sound "wants" to travel slowly).

**Q**: **What type of reflector is the sea surface modelled as?**
**A**: The sea surface is modelled as a perfect reflector, as the reflection coefficient $R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \approx -1$

**Q**: **How can we classify the type of sea bottom observed in sonar imaging?**
**A**: Seafloors of different composites have different reflection coefficient. The reflection coefficient can be estimated by measuring the echo/backscatter intensity, which in turn is used to classify the type of seafloor.

**Q**: **What types of scattering do we get from reflections from rough and vs. smooth surfaces?**
**A**: Smooth surfaces: mostly specular reflections/scattering
Rough surfaces: a combination of specular and diffuse scattering.

**Q**: **What is a coded vs non-coded pulse?**
**A**: A *non-coded* pulse is a pulse of a simple wave-form, like a sine wave of constant frequency. In *coded* pulsing, some modulation occurs during transmission, like a changing frequency or amplitude. An example of a coded pulse is a linear FM sweep, where the transmitted frequency is linearly increased during the transmission of the pulse.

**Q**: **What is range resolution and how are they calculated for coded vs non-coded pulses?**
**A**: Range resolution refers to the ability to distinguish echoes from two separate ranges/depths. For simple, non-coded pulses, this is fundamentally limited by the length of the pulse:

$$\delta R = \frac{cT_p}{2}$$

For coded pulses, the resolution is bandwidth-limited:

$$\delta R = \frac{c}{2B}$$

**Q**: **What is the matched filter and what is it used for?**
**A**: The matched filter convolves the received signal with a conjugated, time-reversed version of the transmitted signal. This is used to improve SNR or range resolution, and is linked to the *processing gain* of the sonar equation.

**Q**: **What is the sonar equation?**
**A**: The sonar equation summarizes the signal contributions from different sources, and can be used to model the total SNR:

$$SNR = Signal - Noise + Gain > Threshold$$

Note: log-scale (Addition!)

**Q**: **What is the beamwidth/direcitvity equation? How do we achieve good directivity?**

**A**:

$$\beta \approx \frac{\lambda}{D}$$

Where $\lambda$ is the wave length and $D$ the aperture size. Good directivity means a small beamwidth. From the equation, this is achieved when the aperture size is grater than the beamwidth ($D \gg \lambda$). Higher frequency $\rightarrow$ narrower beam.

**Q**: **What's important to consider when designing the waveform for a sonar application?**
**A**: We generally want to maximize resolution and SNR. Resolution is inversely proportional to bandwidth, so we want use high bandwidths. At the same time, high frequencies experience greater attenuation and we need to consider the depths we are trying to image. The power of the waveform is proportional to the signal length and amplitude, so increasing these will give better SNR.

**Q**: **Explain the concept of synthetic aperture sonar imaging**
**A**: A "synthetic aperture" is formed along the direction that the vessel travels, by collecting successive pulses. Accurate navigation sensors are required to georeference measurements taken from different times/positions. The echoes from the same seabed-positions are coherently combined over separate pulses. This is analogous to the coherent compounding done in CWPC (in CWPC, we assume the probe is static between transmits).

**Q**: **What are acoustic shadows and when do they occur in sonar imaging?**
**A**: Acoustic shadows appear as dark areas in the ultrasound image, and occur when an area is acoustically occluded by an object with a high reflectance coefficient. This object prevents/blocks the sound from permeating through to the area behind it, resulting in a shadow.

## 5. Doppler imaging

**Q**: **What is doppler ultrasound used for?**
**A**: Doppler ultrasound is used to measure the blood flow in the body, and can be used to diagnose stenosis, detect defects in the heart, and blood flow assessment in general.

**Q**: **What is the doppler effect**
**A**: The doppler effect describes the observed frequency when the sound source is moving. If the source is moving towards the observer, the observed frequency is increased, and it is decreased when the source is moving away (Ex: Ambulance sirens passing by).

**Q**: **How/where does the doppler effect occur in ultrasound imaging?**
**A**: When imaging blood vessels, the moving blood cells cause the doppler effect to occur, as the blood cell acts as both a moving observer and a moving source. As a moving *observer* as the transmitted ultrasound wave propagates through it, and as a moving *source* as part of the wave is reflected by the cell.

**Q**: **What is the doppler shift equation of a moving blood cell?**
**A**: The doppler frequency for an observer moving parallell to the wave direction is given by

$$f_d = f_0 \frac{v}{c}$$

For a moving blood cell, the doppler shift essentially happens twice (back and forth), and the total shift is then

$$f_d = 2f_0 \frac{v}{c}$$

This equation only holds when the wave propagation is parallell to the blood cell velocity direction. To generalize for all directions, the equation is modified to only include the parallell

part:

$$f_d = 2f_0 \frac{v \cdot cos\theta}{c}$$

Where $\theta$ is the angle between the wave direction and the blood velocity direction (beam-to-flow angle).

**Q**: **How is the doppler signal modelled?**
**A**: We model the doppler signal $s_D$ as a combination of signal from the blood itself, clutter and noise:

$$s_D = s_b + s_c + s_n$$

**Q**: **What is clutter, and how do we deal with it in doppler imaging?**
**A**: Clutter is signal from surrounding the vessel walls and other surrounding tissue. We can use a high-pass filter to remove this part of the signal, since the clutter generally has low velocity compared to the blood (giving low doppler frequencies).

**Q**: **How does clutter degrade the results of doppler imaging?**
**A**: When not filtered properly, clutter can partially or totall obscure the signal from the blood, as it is much stronger. It can also create a bias in the velocity estimation, and create sidelobes in the velocity spectrum, further deteriorating the spectrogram quality.

**Q**: **What is CW doppler? What are the benefits and downsides?**
**A**: Continuous Wave doppler is a doppler technique where the ultrasound wave is transmitted continuously (not in pulses). In this case, we need a separate receiver array. Since we need two arrays (which are separated in space), we can only image where their viewing regions overlap.

**Q**: **What is PW doppler?**
**A**: In Pulsed Wave doppler imaging, we use pulses of a given length instead of constinuously transmitting a wave. This allows us to use just a single transducer array.

**Q**: **What is PRF**
**A**: PRF is the "pulse repetition frequency", that is, the reciprocal of the time between two consecutive pulses.

**Q**: **What limits the PRF?**
**A**: The PRF is limited by how far the wave needs to travel ($2 \cdot \text{depth}$) and how quickly it travels ($c$):

$$PRF = \frac{1}{PRT} = \frac{c}{2 \cdot \text{depth}}$$

**Q**: **What is the difference in slow-time and fast-time sampling? Which type is needed for doppler imaging?**
**A**: In *fast-time* sampling, multiple samples are taken in time/depth, for a single pulse/transmit. This is enough to form a single ultrasound image, as seen in previous modules. In other words, fast-time sampling is sufficient for capturing the amplitude of the reflected signals.
With *slow-time* sampling, we observe how the phase of the echoes evolves over time for each point in the scene, over multiple transmits. This phase shift over time is used to calculate the Doppler frequency, which in turn provides an estimate of the velocity of the moving target.

**Q**: **When does aliasing occur and how can we determine a lower bound for the PRF?**
**A**: Aliasing occurs when a signal is undersampled. When undersampling occurs, the original signal can no longer be deterministically reconstructed, and the velocities are misidentified.

**Q**: **How do we avoid aliasing? How is the blood flow velocity related to sampling?**
**A**: The nyquist sampling criteria must be met:

$$f_{PRF} > 2f_d$$

Where $f_d$ is the highest doppler frequency component in the signal. Since the doppler frequency is directly related to the blood velocity ($f_d = 2f_0\frac{v}{c}$), we get the following sampling criteria:

$$f_{PRF} > 4f_0\frac{v_{max}}{c}$$

Where $v_{max}$ is the maximum blood flow velocity.

**Q**: **Why do we need to perform angle correction when doing doppler imaging?**
**A**: The beam-to-flow angle occurs in the doppler frequency equation:

$$f_d = 2f_0\frac{v\cos\theta}{c}$$

To achieve accurate velocity measurements, this angle $\theta$ must be estimated. This is done graphically by manually aligning a line with the blood vessel direction.

**Q**: **How does spectral broadening affect the doppler results and how can we minimize this effect?**
**A**: Spectral broadening results in misidentification of the doppler frequencies, giving us inaccurate velocity measurements. The ability to accurately measure the velocity is related to the strength of the doppler effect, which is maximized when the beam-to-flow angle is low. Generally, we want the beam-to-flow angle to be below 60°.

**Q**: **What is the main limitation of CW doppler?**
**A**: Since the wave is transmitted continuously, CW doppler provides no depth specificity.

**Q**: **What is PSV and EDV, and how are they measured?**
**A**: PSV is the maximum blood flow velocity during a cardiac cycle, while EDV is the velocity at the end of the cardiac cycle. These are measured by observing the doppler spectrogram and identifying the min/max.

**Q**: **When do we use CW doppler and why?**
**A**: CW doppler is used when the expected blood flow velocities are very high. This is because of the max-velocity limitation on PRF for PW doppler, discussed above. CW does not have this limitation.

**Q**: **What is CFI used for?**
**A**: Color Flow Imaging is a semi-quantitative doppler modality and is used to visualize turbulence, acceleration, regions of blood flow and the overall dynamics of the blood flow.

**Q**: **In short, how does CFI work?**
**A**: CFI works by using multiple focused transmits along multible beams/color lines. The collection of transmits/pulses used for a single color line is referred to as a "packet". The blood velocity is estimated around each of the focal areas of the packet pulses. These estimates are then combined and compared to estimate the velocity at each "sample volume".

**Q**: **Which two signal processing methods to process the sample volume data?**
**A**: <u>auto-correlation:</u> the data for each pulse locations is compared between consecutive echoes, meaning the same sample volume is compared to itself at a later echo.
<u>cross-correlation:</u> in this method, different sample volumes are compared, along the same scan line or across scan lines rather than comparing consecutive echoes at the same position.

**Q**: **What is duplex and triplex acquisition?**
**A**: In duplex and triplex acquisition, we perform separate scan sequences for each imaging modality. In the case of triple acquisition, we do:

- B-Mode: regular ultrasound image formation as discussed in previous chapters (no velocity estimation)
- CFI: perform the packet acquisition for sample volumes used in auto/cross-correlation
- PW Doppler: PW pulses at the PRF

**Q**: **How is the <u>direction</u> of blood flow estimated?**
**A**: To estimate the direction of the blood flow, we need to estimate the velocity twice, in two different directions. We do this by transmitting two separate plane waves at different angles.

## 6. Imaging Artifacts

**Q**: **What are the main sources of varying image quality in medical ultrasound?**
**A**:

- Abberations
- Sound speed errors
- Reverberations
- Rib blockages

**Q**: **What are abberations and what causes it?**
**A**: When different parts of the wave front pass through volumes with different material properties, the velocities change in different ways, deforming the wave front, i.e if the wave starts out as circular/diverging, it will appear distorted and no longer circular after passing through an abberating medium.
The wavefront distortion causes arrival time differences, which in turn (if uncompensated for) distorts the image.

**Q**: **What's an example of an abberating medium in the body?**
**A**: Subcutaneous fat tissue is complex and distributed unevenly, causing abberations as the ultrasound propagates through it.

**Q**: **In short, how is abberation compensated for and what critical assumption is made?**
**A**: To compensate for abberation, an adaptive algorithm is used to calculate the time delays necessary to "straighten out" the received wave fronts. The assumption made is that a single time delay can be used to correct for the *two-way* abberation.

**Q**: **How do sound speed errors affect the ultrasound image?**
**A**: In practice, sound speed errors distort the ultrasound image, as the pixel → signal mapping becomes incorrect.

**Q**: **What artifacts can occur when there are strong specular reflections?**
**A**: When the wave hits a specular reflector, its path is perfectly reflected according to Snell's law. This is not taken into account in standard beamforming, and can result in misplaced scatterers, i.e the image can contain structures that are not actually there (or even in the expected view of the array).

**Q**: **What is reverberation? How does this look in the image**
**A**: Reverberations happen when the ultrasound wave is reflected off some object (somewhat

specular), then back to the probe, and back again, etc.
In the image this looks like the structure is repeated multiple times in the behind the actual structure.

**Q**: **What are multi-path reflections?**
**A**: Multi-path reflections occur in SONAR can occur when the sound waves reflect off the seafloor, the ocean surface and inside reflective structures like ships multiple times before returning to the source. This results in defocused areas in the image.

**Q**: **What is Second Harmonics Imaging and why do we use it?**
**A**: In second harmonics imaging, we use the second harmonic frequency instead of the fundamental frequency. This technique significantly improves resolution (higher frequency!). Secondly, since the second harmonic part of the wave is not yet generated near the probe, it experiences less attenuation by the tissue close to the probe, giving a higher quality image.